Estimating Contaminated Stormwater Impacts on Sediment and Fish in Portland Harbor (Lower Willamette River, Oregon)

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ABSTRACT

The main stem Willamette River drains a basin of 32,000 km^2 before reaching a confluence with the Columbia River at Portland, Oregon. For more than 100 years, the heavily industrialized reach between the confluence and Portland has been home to numerous industrial and commercial activities. Recent studies have found highly elevated levels of contaminants (metals, PAHs, PCBs, DDT) in sediment and biota. Because recreational and subsistence fishing are popular in this reach, concerns were raised about human health impacts from consumption of contaminated fish. In 2000, the reach between river miles (RM) 3.5 and 9.5 was designated a federal Superfund site. Before cleanup can take place, ongoing sources of contaminants need to be controlled to ensure cleanup goals can be achieved and maintained. Several potential contaminant sources are being evaluated, including inflows from upstream, in-river (contaminated sediment), and stormwater discharges. Because over 300 private and public stormwater outfalls from an industrialized watershed drain into the site, stormwater runoff was long considered a potentially significant mechanism for transporting contaminants to the site. Three models (stormwater runoff, segmented in-river transport and fate, site-specific food web) were integrated to provide environmental managers with quantitative insights into how stormwater might affect contaminant levels in sediment and fish and to develop stormwater control and management strategies. To understand the role of stormwater relative to other contaminant sources, seven different scenarios were evaluated, using PCB-118 as the exemplar contaminant. At a harbor-wide scale, preliminary results suggest that contaminant levels in stormwater may have little discernible impact on those in sediment. Contaminant levels in fish vary in response to contaminant levels in both stormwater and sediment. Overall, this study suggests that legacy contaminants in sediment, and not those in stormwater, are the dominant source of contamination in fish.

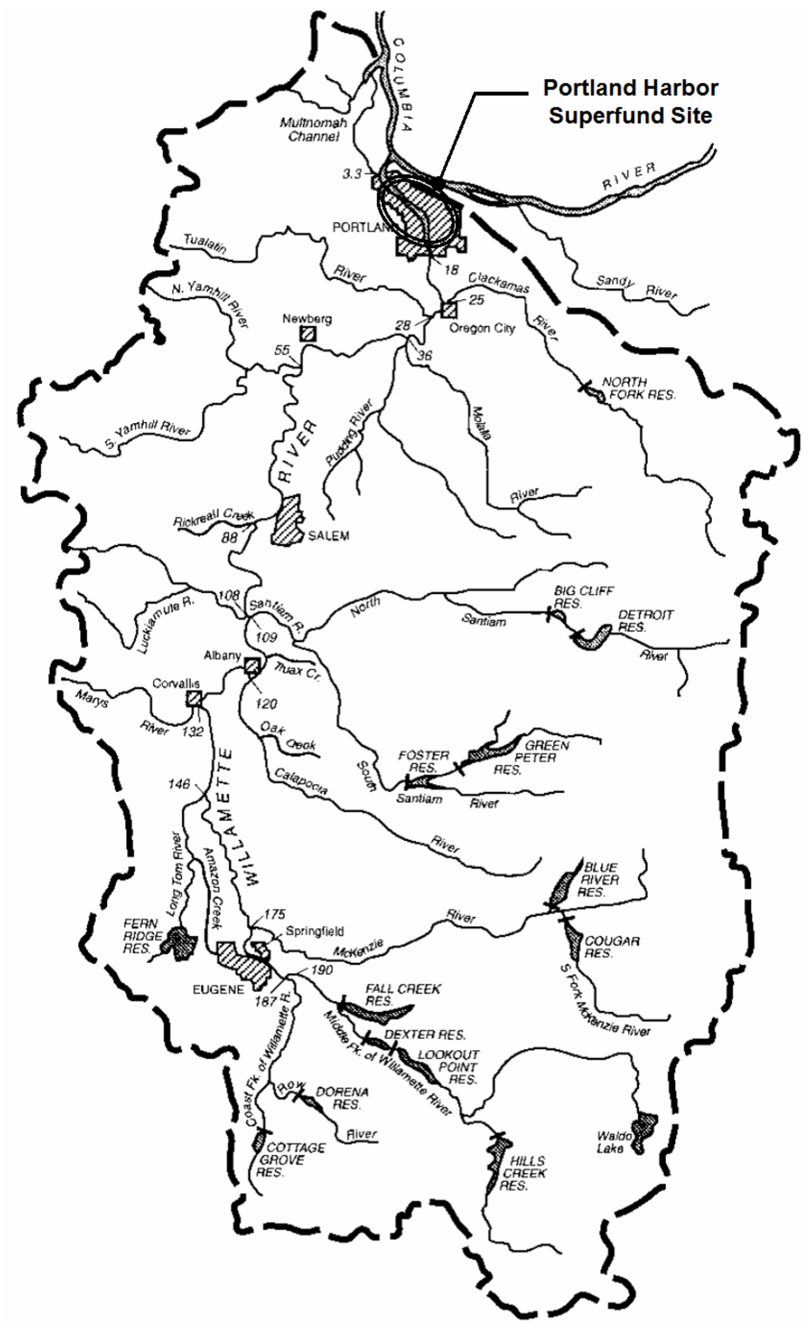
INTRODUCTION

The Willamette River Basin covers approximately 32,000 km^2 of land between the crests of the Cascade and Coast Ranges in northwestern Oregon, USA.[1] Its drainage system is dominated by the Willamette River and its 13 major tributaries (Figure 1). Oregon's three largest urban areas, the cities of Portland, Salem, and Eugene, border the river.[2] The approximately 2 million people (≈70 percent of the state's population) who live or work in the Basin depend on the river for many resources, but also contribute to potential pollution problems associated with many residential, municipal, industrial, or agricultural activities. The lower reach of the Willamette River, which extends from its confluence with the Columbia River to Willamette Falls at approximately RM 26.5 is wide, shallow, slow moving, and tidally influenced as far upstream as RM 15. Between the confluence and RM 11.6 is a highly industrialized area, known as Portland Harbor ("Harbor"), where numerous industrial activities, such as an a oil gasification plant, ship repair facilities, agricultural chemical manufacturing, rail car construction, wood treating facilities, and port activities, have occurred or are occurring (Figure 1).

A joint Oregon Department of Environmental Quality (ODEQ) - U.S. Environmental Protection Agency (USEPA) study of sediment in the Harbor, completed in 1998, found it to be contaminated with polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), pesticides (primarily DDT and its metabolites), herbicides, dioxins/furans, and metals. These findings lead to the reach between RM 3.5 and 9.5 being designated a National Priorities List ("Superfund") site in December 2000; this reach is referred to as the Initial Study Area (ISA). In September 2001, USEPA signed an administrative consent order for the completion of a remedial investigation and feasibility study (RI/FS) within the ISA.[3] Subsequent work reported elevated levels of organic and inorganic contaminants in the tissues of fish resident within the ISA.[4, 5] Because recreational, sport, and subsistence fishing are extremely popular in the lower river and resident species are fished throughout the year, the presence of chemical contaminants in fish has raised concerns about human health impacts from consumption of fish caught within the ISA.

Chemical contaminants detected in the ISA may come from several sources, including upstream (i.e., "background" loads with respect to the ISA), in-river (i.e., from sediment contaminated by past (legacy) or current (continual or episodic) releases), atmospheric deposition of aerosol or gas phase contaminants directly to surface water, or stormwater discharges (which includes a contribution from atmospheric deposition to land). Because over 300 private and public stormwater outfalls, including storm drains and combined sewer overflows, enter the ISA, stormwater runoff is considered a potentially significant mechanism for transporting chemical contaminants to the ISA from the highly urbanized and industrialized upland areas within its watershed. While empirical stormwater contaminant concentration data were being gathered, a cost-effective means was sought to provide environmental managers with initial quantitative insights into how stormwater discharges, as well as any stormwater control and management strategies, could affect chemical levels in sediment and fish within the ISA. A stormwater runoff model (to estimate loads to the river), a multi-segment transport and fate model (to estimate the movement and disposition of contaminants within the river), and a site-specific food web biomagnification model (to link water and sediment concentrations to levels in fish) were integrated for this purpose. These models were used to explore seven scenarios related to the impact of various sources on contaminant levels in sediment and fish tissue.

Figure 1: Location of the Portland Harbor Superfund Site within the Willamette Basin



METHODS

Contaminant of Interest

Although a number of persistent, hydrophobic, organic chemicals are present in the Harbor, polychlorinated biphenyls (PCBs) are the primary risk drivers. PCBs are a class of 209 individual compounds (or congeners) that vary widely in their chemical and toxicological properties. However, for logistical, data availability, and toxicological reasons, it is neither possible nor necessary to model all 209 congeners. Of the 209, a dozen are now considered to be "dioxin-like" because of their toxicity and certain features of their structure which make them similar to 2,3,7,8-tetrachlorodibenzo-p-dioxin (2378-TCDD).[6] The exemplar for this study, PCB-118 [CASRN 31508-00-6], a mono-*ortho*-substituted congener 2,3’4,4’5-pentachlorobiphenyl, was selected primarily on the basis of its toxicity relative to 2378-TCDD, its occurrence in various media (sediment, water, air, tissue) within the Harbor and the Basin, and its documented presence in stormwater at other localities. Aroclors (commercial mixtures of various congeners) were not included because they are not physicochemically distinct and can undergo composition changes in the environment after release. Although PCB-118 is not as toxic as other dioxin-like congeners, it is typically present in the Harbor and Basin environments in much greater mass, making it a significant contributor to total toxicity. For example, in smallmouth bass tissue collected within the Harbor, it is the second greatest contributor, after PCB-126, to the potential for dioxin-like toxicity. It was also found to be the third most abundant congener in fish tissue and clearly present in surface water.[4, 7] Because of their physicochemical similarities, the environmental fate of PCB-118 is a good indicator for that of PCB-126, which is typically found at much lower, and thus more challenging to quantify, concentrations.[8] In sampling conducted in Oregon as part of the National Dioxin Air Monitoring Network (NDAMN) program, PCB-118 was the congener found to be present within the Basin at the highest concentration.[9] In other localities, PCB-118 has been found to be prominent in urban stormwater, one of the congeners with the highest concentrations in water pollution control plant (WPCP) discharges, and a significant portion of the total PCB load in street dust that may ultimately become a component of stormwater runoff.[10, 11, 12]

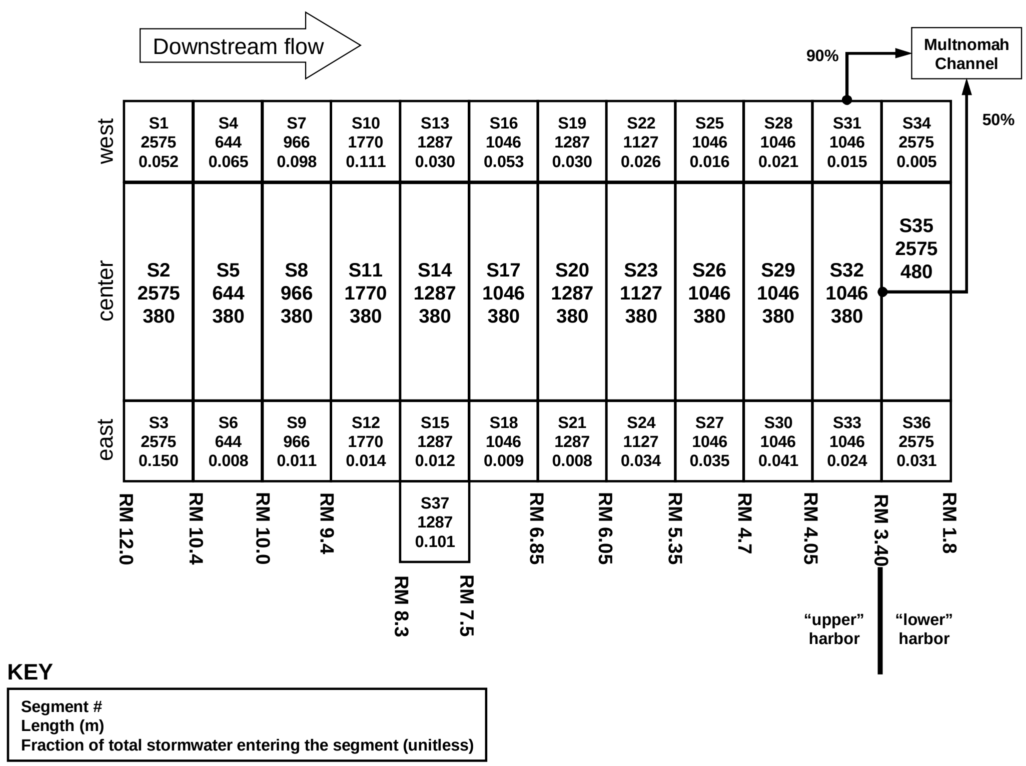
Model System

The impact of episodic and transient releases of chemicals conveyed by stormwater may be more “memorable” in sediment and fish tissue because the time constant of response is longer in these media than in surface water. It is thus important to provide simultaneous, time-dependent estimates of chemical concentrations in all media (sediment, surface water, and tissues of aquatic organisms) that may be affected by stormwater discharges. The overall model design responds to this specification by providing outputs from a stormwater loading model to a mass balance transport and fate model which then feeds sediment and water concentration estimates to a Harbor-specific food web biomagnification model to produce estimates of chemical concentrations in tissues of various aquatic biota. The rate constant transport and food web models assess the distribution of persistent organic chemicals in abiotic and biotic media primarily as a function of the octanol-water partition coefficient. Similar models have been successfully applied to a variety of chemical issues in lakes, rivers, and marine environments.[13, 14] These dynamic non-steady-state models are implemented in Visual Basic® using forward Euler integration, allowing changes in sediment, water, and tissue concentrations to be tracked both over time and at steady-state.[14, 15] Because of the half-life of PCB-118, these models are designed to simulate conditions daily for up to 20 years (7,300 days). The transport and fate model uses a *d*t of 0.01 to meet the Courant criterion, awhile the food web model uses a *d*t of 1.0 for consistency with its rate constants.

Model Domain and Structure

The model domain extends from RM 12.0 to RM 1.8 along the mainstem of the Willamette River (Figure 1). This domain is divided into 36 rectangular segments (Figure 2). Placement of these divisions was informed by the location of sediment management units and knowledge of areas favoring erosion or deposition, as well as of physical features such as habitat areas, grain size, modeled bottom shear forces, river bathymetry and the presence of the shipping channel. Parameters that would affect total flows and the amount of flow diverted down Multnomah Channel include relative stage of the tides in St. Helens and Portland, flow in the Columbia River, and Willamette River flow into the Harbor. It was assumed, based on limited data, that 90 percent of the flow from segment 31 and 50 percent from segment 32 is diverted from the main river into Multnomah Channel. There is also a significant change in hydraulic cross section at approximately RM 3.0, where the Multnomah Channel connects with the mainstem.[16] There are 33 segments located upstream (the "upper" harbor) and 3 segments located downstream (the

Figure 2: Spatial arrangement and key physical dimensions of river segments.



"lower" harbor) of this change in hydraulic cross-section. The Shipyard Lagoon, an embayment hydrologically connected to the main river at Segment 15, is an additional segment (Segment 37).

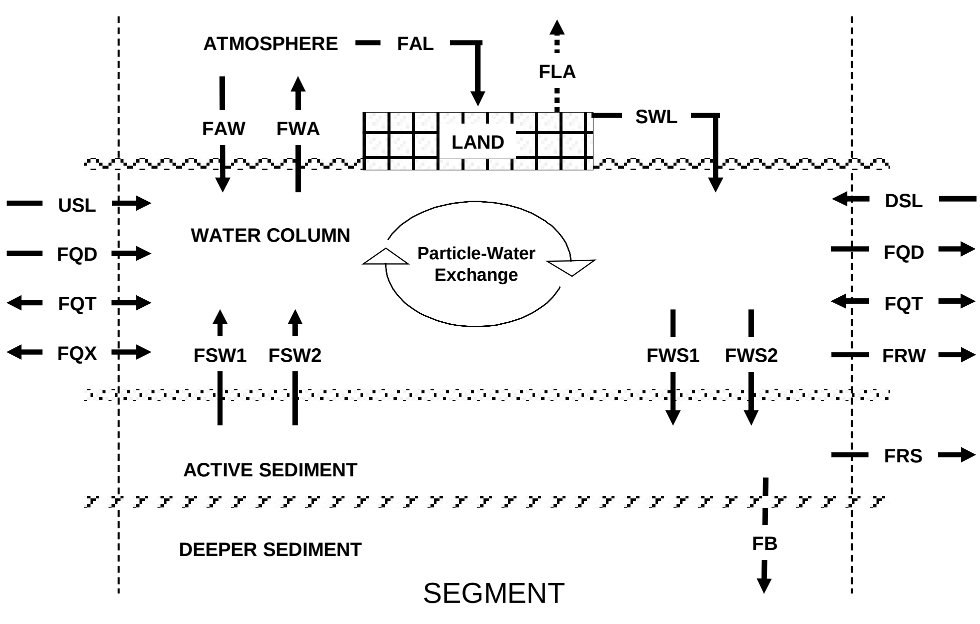
Each segment consists of a water column and an active sediment compartment (Figure 3). These compartments are assumed to be homogeneously mixed. Harbor sediments are conceptually divided into active and buried sediment layers. The active sediment layer is the mass of sediment that is actively exchanging chemicals with the water column and Harbor food webs.

The depth of this layer is dependent on bioturbation (vertical movement of sediment by benthic organisms) and mixing driven by tides and river flows. The buried sediment layer consists of any Harbor sediment that is too deep to exchange chemicals with the active sediment layer and water column. The accessible (or active layer) represents those bottom sediments that participate in the exchange of chemical between the water and the sediments. The inaccessible (buried) layer is a sink to the model. Large removal rates of sediment-bound chemical during periods of net sediment erosion are achieved by parameterizing with the high suspended sediment concentrations typically observed under these conditions. The river water is assumed to be well-mixed or homogeneous in composition, thus once the chemical has entered the river its source becomes immaterial (i.e., the chemical "forgets" its origin). This well-mixed assumption is a key simplification. Similarly the bottom sediment is assumed to be a single well-mixed layer of defined depth, beneath which are buried, inaccessible sediments. This is another key simplification. These simplifications are not necessarily a correct representation of sediment dynamics, but are acceptable from a chemical fate perspective.

Transport and Fate Model

Algorithms and variables for the transport and fate model, with the exception of the fluxes noted below, are as described elsewhere.[8] Spatial relationships and values for the key physical variables for each segment are summarized in Figure 2. It is assumed that values for the physical

Figure 3: Schematic representation of fluxes within and between segments.



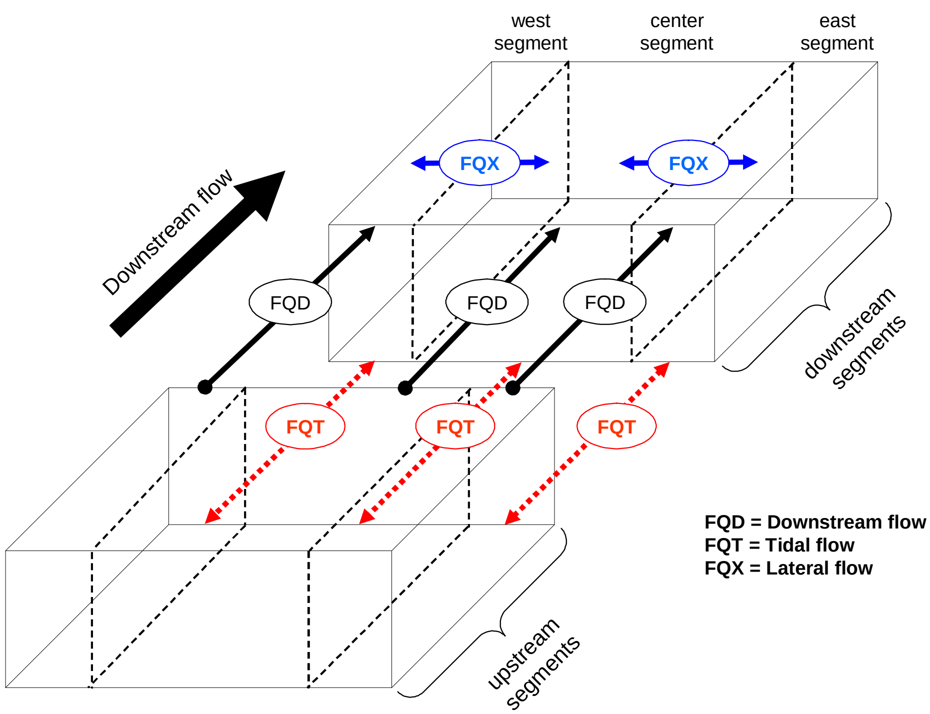
FQD = Downstream flow; FQT = Tidally-driven; FQX = Lateral; FWA = Volatilization from water; FLA = Volatilization from land; FAW = Air deposition to water; FAL = Air deposition to land; FRW = Degradation in water; FRS = Degradation in sediment; FB = Burial; FWS1 = Solids deposition; FWS2 = Water-to-sediment diffusion; FSW1 = Solids resuspension; FSW2 = Sediment-to-water diffusion; SWL = Stormwater load to water

variables in the model (e.g., segment width, water velocity, solids settling rate, etc.) remain constant regardless of the chemical being modeled. In other words, different chemicals could not experience physically different model rivers.

The water and sediment compartments in each segment are acted upon by the same number and type of chemical input and output fluxes (Figure 3). Inputs to the water column include resuspension of sorbed chemicals from sediment (FSW1), diffusion of dissolved chemicals from sediment (FSW2), and downstream, lateral, and tidally-driven fluxes (FQD, FQX, FQT). Loads to the water column from sources external to the model domain include those from stormwater (SWL), upstream (USL), and downstream (DSL) sources, as well as deposition direct from the atmosphere to water (FAW); SWL combines contributions from land-based sources with deposition from the air to land (FAL) within the ISA watershed (SWL is estimated by the stormwater GRID model). Re-volatilization of contaminants from land to air (FAL) is conceptualized but not quantified in the model. Outputs from the water compartment include volatilization to the atmosphere (FWA), outflow of particulate and dissolved chemicals downstream or laterally (FQD, FQX), deposition of particle-bound chemicals to the active sediment layer (FWS1), diffusion of dissolved chemicals to the active sediment layer (FWS2), and degradation of particulate and dissolved chemicals (FRW). Inputs to the active sediment layer include deposition of particle-bound chemicals from the water column (FWS1) and diffusion of dissolved chemicals from the water column (FWS2). Output fluxes from the active sediment layer include resuspension of sorbed chemicals to the water column (FSW1), diffusion of dissolved chemicals to the water column (FSW2), burial of sorbed chemicals as inaccessible deep sediment (FB), and degradation of sorbed and dissolved chemicals in sediment (FRS).

Mass movement between segments occurs through movement of water and of particles suspended in water; bed load transport is not simulated. Three fluxes control such movement between segments: (1) downstream flow of the mainstem Willamette River (FQD), (2) tidally-driven flows between segments up- and downstream of one another (FQT), and (3) lateral flows

Figure 4: Schematic representation of fluxes between segments.



between adjacent segments (FQX) (Figure 4). Neither tidal nor lateral flows occur unless there is a concentration gradient between their respective segments.

Because the model divides the width of the river into three parallel segments, the total downstream flow, velocity, and hydraulic area of the river must be apportioned to each segment while maintaining the relationship U = Q/XSA. Apportionment involved estimating the total hydraulic cross-section area as a function of river stage, based on a regression relationship developed from USGS data collected at RM 12.8, then velocity as a function of cross-section area and flow. Although segments have differing lengths, initial runs indicated that transport and fate model performance would not be compromised if the width of all side segments was the same (10 m), as well as that for all center segments (380 m in upper harbor, 480 m in the lower harbor). The width of side segments was selected to encompass the more biologically relevant areas of the river. In addition, a distinct and persistent period of relative high water occurs in the lower Willamette from late May through June when spring freshet-driven high flows in the Columbia increase the hydraulic head at the confluence of the two rivers and cause the flow of the Willamette to be detained.[3] When this occurs, water volume in the Willamette is increased irrespective of its flow. To account for this detention, channel cross section area was estimated as a function of river stage, rather than flow, with stage estimated from USGS observations at RM 12.8 between 1987 and 2005. Velocity apportionment was based on the assumption, using data collected in the lower harbor, that velocity in side segments (those in contact with the shore and in shallower water) will be approximately 75% of that in the center (main channel) segment.[17] A value for UAF in the center segment was estimated by numerical approximation so that the relationship U = Q/XSA was maintained and the sum of the flows across each segment equals that for the entire river. Apportionment was not applied to the Shipyard Lagoon (Segment 37).

The movement of a chemical laterally between adjacent segments was estimated as a function of the relative difference in chemical concentration between the side segments and the average concentration across all three adjacent segments (Figure 4). Chemical movement into and out of the Lagoon (Segment 37) is modeled in this rudimentary manner, which increases uncertainty in the model's ability to correctly represent the hydrodynamics of this embayment.

The tidal range at the Pacific Ocean is approximately 1.5 m and there are two high tides and two low tides daily. The tidal "wave" coming up the Columbia River can result in flow reversals in the Willamette River near its mouth and within Multnomah Channel under certain river stage, river flow, and tidal conditions.[3, 18] During summer low-flow periods, tidal effects can cause flow reversals in the Willamette River below RM 15. Such reversals are most likely during times of extreme low discharge combined with a large variation in tide levels, which can occur in late summer to early fall. As river stage rises, this tidal effect is gradually dampened and disappears at river levels around 10 feet Columbia River Datum. These flow reversals could serve to transport (via tidal back-flow) sediment-bound chemicals from a chemical source downstream of the domain into segments 34-36. The tidally-driven movement of a chemical between segments (Figure 4) is assumed to be a function of the relative difference in chemical concentration between upstream and downstream segments, with the equation structured so that tidal reversals, of up to $\approx$ -3,500 $ft^3\ s^{-1}$, occur only between mid-June to mid-October, during summer low flow.

External Load Estimates

Although various external loads from various sources (e.g., from overland flows, outfalls, groundwater upwelling, bank erosion, etc.) are possible, this study focused on three: those from stormwater (SWL), upstream (USL) and downstream (DSL). The load resulting from deposition from the atmosphere to land would be captured in the stormwater load, and deposition to water (FAW) was estimated to be minimal in relation to the river's flow and volume. Any direct loading of the active sediment layer by, for example, a legacy contaminant moving upward from a deeper sediment layer, was also not considered. A USL was applied only to Segments 1 - 3 as a function of mainstem flow and the measured surface water concentration at or near RM 12.0, the southern boundary of the model domain. A DSL was applied only to Segments 34 - 36 as a function of tidally-driven backflows and the measured surface water concentration at or below RM 1.8, the northern boundary of the model domain.[3]

The PCB-118 load conveyed by stormwater (SWL) from land to a given segment of the river was estimated with a GRID model for the Portland Harbor watershed and preliminary measurements of PCB-118 concentrations in stormwater.[3,19] The measured concentration in stormwater was assumed to result from atmospheric deposition to land and any contaminant load from land-based sources, and the fraction of total stormwater flow discharging to that segment (c.f., Figure 2). The GRID model is a geographic information system (GIS)-based reconnaissance-level pollutant-loading model.[19] The model uses an array of grid cells into which detailed GIS and other spatial data are compiled. The grid size used in the model is 100-foot by 100-foot. Data compiled for each grid cell include precipitation, pervious/impervious area, and zoning area (or actual land use). With these data, a set of runoff equations is then applied to calculate runoff volumes for each grid cell. Within the GRID model used for this study, the effective stormwater runoff is calculated, by model segment, using a simplified runoff coefficient equation method. The runoff coefficient is the overall ratio of stormwater runoff to rainfall and is proportional to the percentage of impervious surface area within a basin. The modeled area is approximately 58.53 km^2 (22.6 mi^2), which is slightly larger than the 44.03 km^2 (17 mi^2) identified in the introduction as the Portland Harbor Study Area.

Stormwater data are currently being collected at various land use types that represent significant acreage within the Portland Harbor drainage area. The number of monitoring stations for each land use was selected based on the expected variability of pollutant concentrations: open space (1 station), residential (2 stations), major transportation (2 stations), light industrial (3 stations), and heavy industrial (9 stations). Additionally, there were 9 stations designated as having potentially unique land use, and therefore unique loading, that were also monitored. Three event-mean composite samples are targeted for each monitoring station. Concentration data used to calculate overall loading for this current evaluation were based on a data set that generally represented only one to two events at each station. Further refinement of loading rates will be conducted after the full data set has been obtained and evaluated.

To calculate loading by model segment, the effective runoff modeled for that segment was apportioned by the percent acreage of land use within that segment's drainage area and then multiplied by the estimated PCB-118 concentration for that land use. Each land use loading (volume x concentration) within a given segment was then summed to provide the overall segment load. Further refinements to load estimates are expected to include modeled runoff for each land use in each segment to provide a greater level of accuracy in overall load estimates.

Food Web Model

Algorithms and variables for the food web model are described elsewhere.[15, 20] The model food web includes ten aquatic species that surveys and sampling activities have found in the Harbor, particularly its near-shore areas.[3, 5] These include phytoplankton, zooplankton, filter-feeding benthic invertebrates (clams, *Corbicula*), benthic consumer invertebrates (oligochaete worms), epibenthic consumer invertebrates (crayfish), forage fish (sculpin, *Cottus* sp.), benthivorous fish (largescale sucker, *Catostomus macrocheilus*), omnivorous fish (common carp, *Cyprinus carpio*), carnivorous fish (smallmouth bass, *Micropterus dolomieui*), and piscivorous fish (northern pikeminnow, *Ptychocheilus oregonensis*). The feeding relationships between these species were based on literature surveys and the results of stomach content analyses of fish collected within the Harbor.

RESULTS AND DISCUSSION

Seven scenarios were evaluated regarding the impact of various sources and combinations of sources on contaminant levels in sediment and fish tissue. Observed and estimated concentrations in sediment and fish tissue under these various scenarios are summarized in Table 1.

(1) By assuming there were no stormwater loads and that sediment within the Harbor was “clean” (hypothetically zero contamination), this scenario explored the impact of upstream sources alone could have on contaminant levels in sediment and fish.

(2) By assuming sediment within the Harbor was “clean” (hypothetically zero contamination), this scenario explored the impact of combined upstream sources and stormwater loads on contaminant levels in sediment and fish.

(3) By assuming that sediment within the Harbor was uniformly contaminated no greater than an acceptable level, this scenario explored whether impacts to sediment and fish from combined upstream sources, stormwater load, and an acceptable sediment load.

(4) By assuming no stormwater loads and that sediment within the Harbor was uniformly contaminated at the current Harbor-wide average less “hot spots” {i.e., to represent what the average sediment concentration might be if “hot spots” were removed, the initial total concentration in sediment was derived by averaging the 90th percentile of all PCB 118 sediment data for the harbor area within the model domain}, this scenario explored impacts to sediment and fish from upstream sources given a potentially achievable sediment load.

(5) By including stormwater loads and assuming that sediment within the Harbor was uniformly contaminated at the current Harbor-wide average less “hot spots”, this scenario explored whether impacts to sediment and fish from combined upstream sources and

stormwater loads given a potentially achievable sediment load.

(6) By assuming no stormwater loads and with sediment contamination at presently observed levels, this scenario explored impacts to sediment and fish from upstream sources given this current level of contamination.

(7) By including stormwater loads and with sediment contamination at presently observed levels, this scenario explored impacts to sediment and fish from combined upstream sources and stormwater loads given this current level of contamination.

Table 1. Summary of estimated PCB-118 concentrations in sediment and fish by scenario.

Scenario	Description	CONCENTRATION (μg kg^{-1}) [(a)]	
		SEDIMENT (mean) [(b)]	FISH TISSUE (mean) [(b)]
1	Upstream load (given CWT_{up} = 0.014 ng L^{-1}), no stormwater load, no sediment contamination (CST = 0)	$3.5\times10^{-6} \pm 1.3\times10^{-6}$ 8.7×10^{-9} (Lagoon)	5.3 ± 0.9 0.1 (Lagoon)
2	Upstream load, stormwater load [(c)], no sediment contamination (CST = 0)	$4.6\times10^{-6} \pm 2.9\times10^{-6}$ 6.5×10^{-7} (Lagoon)	6.1 ± 2.2 5.3 (Lagoon)
3	Upstream load, stormwater load [(c)], initial sediment contamination at the SLV (CST = SLV) [(d, e)]	0.1 ± 0.002 0.1 (Lagoon)	6.3 ± 2.2 5.4 (Lagoon)
4	Upstream load, no stormwater load, initial sediment contamination at harbor average less "hot spots" (CST = 2.86 μg kg^{-1}) [(d)]	2.8 ± 0.1 2.8 (Lagoon)	9.7 ± 1.0 4.6 (Lagoon)
5	Upstream load, stormwater load [(c)], initial sediment contamination at harbor average less "hot spots" (CST = 2.86 μg kg^{-1}) [(d)]	2.8 ± 0.1 2.8 (Lagoon)	10.5 ± 2.2 9.8 (Lagoon)
6	Upstream load, no stormwater load, sediment contamination at presently observed levels [(d)]	22.4 ± 81.1 *16.7 ± 44.5* 8.4 (Lagoon) *8.8*	40.4 ± 128.0 *31.2 ± 14.9* 13.5 (Lagoon) *22.9 ± 14.2*
7	Upstream load, stormwater load [(c)], sediment contamination at presently observed levels [(d)]	22.4 ± 81.1 *16.7 ± 44.5* 5.6 (Lagoon) *8.8*	41.1 ± 128.4 *31.2 ± 14.9* 22.1 (Lagoon) *22.9 ± 14.2*
	Public health protection levels	SLV = 0.12 [(e)]	FCAV = 5.9 [(f)] ATL = 2.1 [(g)]

(a) Observed sediment and fish tissue concentrations are shown in italics.

(b) Mean (± 1 standard deviation) of estimated concentrations between days 2000-3000 (near steady-state) of the model simulation.

[c] Total load based on stormwater concentrations.
[d] Initial total concentration in sediment. Initial concentration declines over course of simulation.
[e] SLV = Screening level value for sediment for PCB-118, cancer basis.[21]
[f] FCAV = Fish consumption advisory value for general human consumption, total PCBs, non-cancer basis.[22] Cancer-based FCAV is 1.5 μg kg^{-1}.
[g] ATL = Acceptable tissue level for general human consumption, total PCBs, cancer basis.[21]

Current mean PCB-118 concentrations in total sediment (CST), in surface water upstream of the model domain (CWT_{up}), and in fish within the Harbor were estimated using Portland Harbor Round 2 sediment and surface water data and fish tissue data collected by others (Table 2). No data were available with which to estimate total water concentrations downstream (CWT_{dn}) of Segments 34-36. Results from Scenario 7, replicating current conditions, were compared to these measured values where possible to partially validate the model's estimates of PCB-118 levels in fish and sediment on a Harbor-wide average basis.

Table 2. Summary of PCB-118 concentrations observed in various media.

Media	Concentration [§ *]
Concentration in surface water upstream (CWT_{up}) (pg L^{-1}) [a]	10.72 ± 9.56 4.34 ± 2.63
Concentration in fish tissue (ng kg^{-1})	31271.0 ± 14986.4 [b] 35500.0 ± 13010.8 [c]
Concentration in sediment (μg kg^{-1})	16.70 ± 44.54 [d] 14.63 ± 57.53 [e]
Concentration in air (near Corvallis, OR) (fg m^{-3}) [f]	1437.9 ± 590.7

§ Values shown are arithmetic mean ± one standard deviation.
* Upper value is concentration on solid fraction; Lower value is concentration in dissolved fraction.
[a] Portland Harbor, Round 2 (Dec 2004) data.[5]
[b] Portland Harbor, Round 1 (Apr 2003) data, smallmouth bass only.[5]
[c] Portland Harbor, RM 3 - 15, smallmouth bass only.[4]
[d] Portland Harbor, Round 1 (Apr 2003) data.[5]
[e] Portland Harbor, Round 2 (Aug 2005) data, PCB 106 & 118 mixture.[5]
[f] National Dioxin Air Monitoring Network (NDAMN) site near Marvel Ranch, Oregon.[9]

The smallmouth bass (SMB), an upper trophic level carnivorous species popular with recreational and subsistence anglers, was selected as a representative species for this study. Portland Harbor Round 1 tissue data were used to estimate the Harbor-wide mean total contaminant concentration in this species.[5] Levels of specific PCB congeners in smallmouth bass collected in the Harbor have also been reported elsewhere.[4] As was the case with sediment, the model could not replicate the presently observed spatial distribution and magnitude of fish tissue concentrations on a segment-by-segment basis simply by applying various external loads. Interpretation of tissue results was also hampered by too few fish samples relative to the size of the Harbor and lack of samples in specific segments (a consequence of segments having been delineated after collection of Round 2 samples), which necessitated representing tissue levels in some segments based on width-of-river composite samples. Samples in the Lagoon (Segment 37), for example, were all taken near its mouth and may thus not fully represent conditions near the stormwater outfalls located at its head.

For Scenarios 6 and 7 the initial mass of contaminant in the sediment compartment of each segment was adjusted until estimated sediment concentrations (CST) closely approximated observed mean values. Alignment between modeled and observed CST values across segments was assessed by the sum of the square of their differences (ΣSQDiff); values closer to zero indicate greater alignment. Because the highly heterogeneous pattern of legacy contamination observed in sediment is due, not to natural physical processes, but to unique anthropogenic releases, the model could not replicate the presently observed spatial distribution and magnitude of sediment concentrations on a segment-by-segment basis by applying only continuous upstream or stormwater loads.

When interpreting the model estimates for each scenario, potential impacts to sediment were evaluated using the ODEQ screening level value (SLV) for sediment (Table A-1b).[21] Potential impacts to fish consumers were assessed (for cancer outcomes) with the ODEQ acceptable tissue level (ATL) for the general human population (Table A-3b) [21] and (for non-cancer outcomes) with the USEPA fish consumption advisory value (FCAV) for unrestricted fish consumption by the general human population.[22] The FCAV is on a total PCB basis and therefore would be higher than one for any single PCB congener.

Discussion

With only an upstream load (Scenario 1), the Harbor-wide mean sediment concentration is below the SLV and the Harbor-wide mean fish tissue concentration is below the FCAV, but not the ATL in the main river; it is below both in the Lagoon (Segment 37). Upstream sources alone appear capable of raising fish tissue concentrations to near or above levels of concern. This is consistent with the finding of elevated PCB levels in fish from the upper Willamette River.[23]

The addition of a stormwater load (Scenario 2) has no discernable impact on sediment concentrations but increases fish tissue levels in the main river by ≈ 14% and those in the Lagoon by a factor of ≈ 50. These elevated levels in fish are likely attributable to the Lagoon being a backwater embayment of the main channel within which water movement, and thus any contaminant flushing or dilution, is much more restricted than in the faster-flowing main river. The model segment representing the Lagoon also receives the second highest fraction (10.1%) of total stormwater discharges to the Harbor. This combination of low water movement and high loading potentially contribute to elevated tissue levels.

Adding sediment contamination at the level of the SLV (Scenario 3) increases, with respect to Scenario 2, fish tissue levels in both the main river and the Lagoon by ≈ 2-3%. This suggests that if it were possible to reduce all sediment levels to the SLV, impacts on fish tissue would be only slightly greater than those attributable to a combination of upstream and stormwater loads.

Adding sediment contamination at the level of the Harbor-wide average less “hot spots”, but removing the stormwater load (Scenario 4), results in a large (≈ 35%) increase, with respect to Scenario 3, in fish tissue levels in the main river. This suggests that, as sediment concentrations rise, they providing an increasing source of contaminants to fish. In the Lagoon, however, the fish tissue level decreases by ≈ 15% (to below the FCAV), suggesting that, within the restricted waters of the Lagoon, stormwater loads could be having an impact on contaminant levels in fish. In all remaining scenarios, the SLV, FCAV, and ATL was always exceeded.

With sediment contamination at the level of the Harbor-wide average less “hot spots” and a stormwater load (Scenario 5), fish tissue levels in the main river increase ≈ 8% relative to Scenario 4, while those in the Lagoon show a ≈ 53% increase. This suggests that stormwater loads are likely to have much less impact on fish (relative to sediments?)in the open waters of the main river and a much greater one in the confined waters of the Lagoon.

With sediment contamination at currently observed levels and no stormwater load (Scenario 6), fish tissue levels in the main river increase significantly (≈ 76%) relative to Scenario 4, while those in the Lagoon show a ≈ 66% increase. This reinforces the suggestion that, as sediment concentrations rise, they providing an increasing source of contaminants to fish.

With sediment contamination at currently observed levels and a stormwater load (Scenario 7), fish tissue levels in the main river increase slightly (≈ 2%) relative to Scenario 6, while those in the Lagoon show a ≈ 39% increase. This reinforces the suggestion that stormwater loads are likely to have much greater impact on fish tissue levels in the confined waters of the Lagoon than in the open waters of the main river.

Summary

On a harbor-wide scale, results suggest that contaminant levels in stormwater may have little discernible impact on those in sediment and only a small (< 10%) impact on contaminant levels in fish tissue within the main river. In the confined waters of the Lagoon, however, and subject to the greater uncertainty in model estimates for this embayment, stormwater loads could have a larger (> 50%) impact. In the main river, legacy contamination in sediment, and not the contaminant load in stormwater, is likely the dominant source of contamination in fish. This suggests that, in response to fish consumption concerns, the most apparent gains from enhanced stormwater management and control efforts will likely occur in the Lagoon. In the main river, where other sources may have a greater impact on fish tissue, such efforts would show more modest results. Further refinements of stormwater loading estimates, including development of land use loading rates based on a broader data set and modeling of effective runoff by land use for each segment, will be conducted for future evaluations of in-river effects.

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this paper. All views or opinions expressed herein are solely those of the authors and do not necessarily represent Oregon Department of Environmental Quality policy or guidance, or those of any other public or private entity. No official endorsement is implied or is to be inferred.

REFERENCES

1. Ulrich, M.A.; Wentz, D.A. *Environmental Setting of the Willamette Basin, Oregon*; U.S. Geological Survey; U.S. Government Printing Office: Portland, OR, 1999; Water Resources Investigations Report 97-4082-A.

2. Altman, B.; Henson, C.M.; Waite, I.R. *Summary of Information on Aquatic Biota and Their Habitats in the Willamette Basin, Oregon, through 1995;* U.S. Geological Survey; U.S. Government Printing Office: Portland, OR, 1997; Water-Resources Investigations Report 97-4023.

3. *Portland Harbor RI/FS Programmatic Work Plan*; Lower Willamette Group: Portland, OR (http://yosemite.epa.gov/R10/CLEANUP.NSF/ ph/Technical+Documents).

4. Sethajintanin, D.; Anderson, K.A. *Environ Sci Technol*, **2006**, 40, 3689-3695.

5. U.S. Environmental Protection Agency, Portland Harbor Cleanup Site, Technical Document Repository. See http://yosemite.epa.gov/R10/CLEANUP.NSF/ph/ Technical+Documents (accessed November 2006).

6. Van den Berg, M.; Birnbaumet, L.S.; Denison, M.; De Vito, M.; Farland, W.; Feeley, M.; Fiedler, H.; Hakansson, H.; Hanberg, A.; Haws, L.; Rose, M.; Safe, S.; Schrenk, D.; Tohyama, C.; Tritscher, A.; Tuomisto, J.; Tysklind, M.; Walker, N.; Peterson, R.E. *Toxicol. Sci.* **2006**, *93*, 223-241.

7. Sethajintanin, D.; Johnson, E.R.; Loper, B.R.; Anderson, K.A. *Arch Environ Contam Toxicol* **2004**, 46, 114-123.

8. Davis, J.A. *Environ Toxicol Chem* **2004**, 23, 2396-2409.

9. Cleverly, D.; Ferrario, J.; Byrne, C.; Riggs, K.; Joseph, D.; Hartford, P. *Environ Sci Technol* **2007**, 41, 1537-1544.

10. Rossi, L.; de Alencastro, L.; Kupper, T.; Tarradellas.; J. *Sci Total Environ* **2004**, 322, 179-189.

11. Durrell, G.S.; Lizotte Jr, R.D. *Environ Sci Technol* **1998,** 32, 1022-1031.

12. Loganathan, B.G.; Irvine, K.N.; Kannan, K.; Pragatheeswaran, V.; Sajwan, K.S. *Environ Contam Toxicol* **1997**, 33, 130-140.

13. Gobas, F.A.P.C.; Pasternak, J.P.; Lien, K.; Duncan, R.K. *Environ Sci Technol* **1998,** 32,

2442-2449.

14. Mackay, D.; Sang, S.; Vlahos, P.; Diamond, M.; Gobas, F.; Dolan, D. *J. Great Lakes Res* **1994,** 20, 625-642.

15. Arnot, J.; Gobas, F.A.P.C. 2004. *Environ Toxicol Chem* **2004,** 23, 2343-2355.

16. Laenen, A.; Risley, J.C. *Precipitation-Runoff and Streamflow-Routing Models for the Willamette River Basin, Oregon*; U.S. Geological Survey; U.S. Government Printing Office: Portland, OR, 1995; Water-Resources Investigations Report 95-4284.

17. Parsons Brinkerhoff Technical Paper. See http://www.pbworld.com/library/ technical_papers/pdf/14_AnInlandTombolo.pdf (accessed October 2006).

18. Caldwell, J.M.; Doyle, M.C. *Sediment oxygen demand in the Lower Willamette River, Oregon;* U.S. Geological Survey; U.S. Government Printing Office: Portland, OR, 1995; Water-Resources Investigations Report 95-4196.

19. *Various TSS analyses and comparisons - Portland Harbor and Willamette Mainstem.* Systems Analysis Group, Bureau of Environmental Services, City of Portland, Oregon (Liebe, M.; Savage, G. Memorandum to dated 11 October 2006).

20. Gobas, F.A.P.C.; Arnot, J. *San Francisco Bay PCB Food Web Bioaccumulation Model: Final Technical Report;* Clean Estuary Partnership, San Francisco, CA, 2005; CEP Task 4.27 (www.cleanestuary.com/publications/).

21. Oregon Department of Environmental Quality, Guidelines for Assessing Bioaccumulative Chemicals of Concern in Sediment (Final). See http://www.deq.state.or.us/wmc/pubs/ docs/cu/GuidelinesAssessingBioaccumulativeChemicalsinSediment.pdf (accessed December 2007).

22. *Guidance for Assessing Chemical Contaminant Data for Use in Fish Advisories, Volume 2;* Office of Water, U.S. Environmental Protection Agency; U.S. Government Printing Office, Washington, DC, 2000; EPA 823-B-00-008.

23. Henny, C.J.; Kaiser, J.L.; Grove, R.A.; Bentley, V.R.; Elliott J.E. *Environ. Mon. Assess.* **2003**, 84, 275-315.

KEYWORDS

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